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European Patent Office
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(11) EP 0 963 040 A2

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
08.12.1999 Bulletin 1999/49

(51) Int. Cl.⁶: H03H 9/17

(21) Application number: 99104070.0

(22) Date of filing: 17.03.1999

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 02.06.1998 US 88964

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(54) **Acoustic resonator and method for making the same**

(57) An acoustical resonator[20, 40, 110] and a method for making the same. A resonator according to the present invention includes a layer of piezoelectric material[22, 42, 112] sandwiched between first and second electrodes. The first electrode[23, 45, 111] includes a conducting sheet having a RMS variation in height of less than 2 μ m. The resonator bridges a cavity[102] in a substrate[101] on which the resonator is constructed. The resonator is constructed by creating a cavity[102] in the substrate[101] and filling the same with a sacrificial material [105] that can be rapidly removed from the cavity[102] after the deposition of the various layers making up the resonator. The surface of the filled cavity[102] is polished to provide a RMS variation in height of less than 0.5 μ m. The first electrode[23, 45, 111] is deposited on the polished surface to a thickness that assures that the RMS variation in height of the metallic layer is less than 2 μ m. The piezoelectric layer is deposited on the first electrode[23, 45, 111] and the second electrode[21, 44, 113] is then deposited on the piezoelectric layer. The sacrificial material [105] is then removed from the cavity[102] by opening vias into the cavity[102] and removing the material through the vias. The preferred sacrificial material [105] is phosphor-silica-glass.

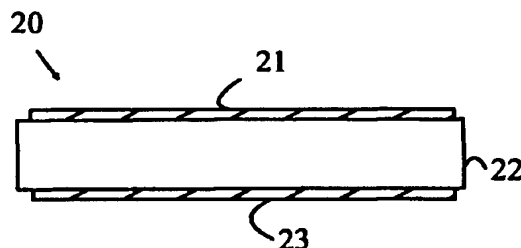


FIGURE 1

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Description

Field of the Invention

[0001] The present invention relates to acoustic resonators, and more particularly, to resonators that may be used as filters for electronic circuits.

Background of the Invention

[0002] The need to reduce the cost and size of electronic equipment has led to a continuing need for smaller filter elements. Consumer electronics such as cellular telephones and miniature radios place severe limitations on both the size and cost of the components contained therein. Many such devices utilize filters that must be tuned to precise frequencies. Hence, there has been a continuing effort to provide inexpensive, compact filter units.

[0003] One class of filter element that has the potential for meeting these needs is constructed from acoustic resonators. These devices use bulk longitudinal acoustic waves in thin film piezoelectric (PZ) material. In one simple configuration, a layer of PZ material is sandwiched between two metal electrodes. The sandwich structure is suspended in air by supporting it around the perimeter. When an electric field is created between the two electrodes via an impressed voltage, the PZ material converts some of the electrical energy into mechanical energy in the form of sound waves. The sound waves propagate in the same direction as the electric field and reflect off of the electrode/air interface.

[0004] At the mechanical resonance, the device appears to be an electronic resonator; hence, the device can act as a filter. The mechanical resonant frequency is that for which the half wavelength of the sound waves propagating in the device is equal to the total thickness of the device for a given phase velocity of sound in the material. Since the velocity of sound is many orders of magnitude smaller than the velocity of light, the resulting resonator can be quite compact. Resonators for applications in the GHz range may be constructed with physical dimensions less than 100 microns in diameter and few microns in thickness.

[0005] At the heart of Thin Film Bulk Acoustic Resonators (FBARs) and Stacked Thin Film Bulk Wave Acoustic Resonators and Filters (SBARs) is a thin sputtered piezoelectric film having a thickness on the order of one to two microns. Electrodes on top and bottom sandwich the piezoelectric acting as electrical leads to provide an electric field through the piezoelectric. The piezoelectric, in turn, converts a fraction of the electric field into a mechanical field. A time varying "stress/strain" field will form in response to a time-varying applied electric field.

[0006] To act as a resonator, the sandwiched piezoelectric film must be suspended in air to provide the air/crystal interface that traps the sound waves within

the film. The device is normally fabricated on the surface of a substrate by depositing a bottom electrode, the PZ layer, and then the top electrode. Hence, an air/crystal interface is already present on the topside of the device. A second air/crystal interface must be provided on the bottom side of the device. There are several prior art approaches for obtaining this second air/crystal interface.

[0007] The first approach involves etching away the wafer that forms the substrate. If the substrate is silicon, the silicon is etched away from the backside using hot KOH. This leaves the resonator constructed on the front side of the wafer supported by its edges. The holes made through such a wafer render the wafer very delicate and highly susceptible to breakage. Furthermore, using wet etches such as KOH with their 54.7 degree etch slope limits the ultimate density and thus the yield of FBAR / SBAR filters on a wafer. For example, devices with lateral dimensions of approximately 150 μm by 150 μm build on a standard 530 μm thick silicon wafer, require a backside etch hole roughly 450 μm by 450 μm . Hence, only about 1/9th of the wafer can be productively utilized.

[0008] The second prior art method for providing an air/crystal interface under the device is to create an air-bridge type FBAR / SBAR device. Typically, a sacrificial layer is first laid down, and the device is then fabricated on top of this sacrificial layer. At or near the end of the process the sacrificial layer is removed. Since all of the processing is done on the front side, this approach does not suffer from having two-sided alignment and large area backside holes. However, this approach is not without inherent difficulties. First, the method is difficult to practice on large devices. Typically, the sacrificial layer is thermally grown SiO_2 which is removed using HF. The etch rate is of the order of 1000 to 3000 $\text{\AA}/\text{minute}$. To etch under device areas that are on the order of 150 μm by 150 μm or larger, an etch time greater than 500 minutes is needed. In addition to being excessively long, the exposure of the metal electrodes to the etchant for periods in excess of 30 minutes leads to the delamination of the metal electrodes from the piezoelectric layer.

[0009] The third prior art approach is referred to as the solidly mounted resonator (SMR), since there are no air gaps under the devices. The large acoustic impedance at the bottom of the device is created by using an acoustic Bragg reflector. The Bragg reflector is made up of layers of alternating high and low acoustic impedance materials. Each thickness is fixed to be at the quarter wavelength of the resonant frequency. With sufficient layers, the effective impedance at the piezoelectric/electrode interface is much higher than the device acoustic impedance, thus trapping the sound waves effectively in the piezoelectric.

[0010] While this approach avoids the problems discussed above in creating a free standing membrane, it has a number of problems. The choice of materials used in the Bragg reflector is limited, since metals can-

not be used for these layers because the metal layers would form parasitic capacitors that degrade the electrical performance of the filters. The degree of difference in the acoustic impedance of layers made from the available dielectric materials is not large. Accordingly, more layers are needed. This complicates the fabrication process as the stress on each layer must be well controlled. After many layers, the device is not conducive to integration with other active elements, since making vias through 10 to 14 layers is difficult. Furthermore, the devices reported to date have significantly lower effective coupling coefficients than devices having air bridges. As a result, filters based on SMRs exhibit reduced effective bandwidths compared to air bridge devices.

[0011] Broadly, it is the object of the present invention to provide an improved FBAR/SBAR device.

[0012] It is a further object of the present invention to provide an FBAR/SBAR device that does not require back etching of the substrate.

[0013] It is a still further object of the present invention to provide an FBAR/SBAR device that does not require excessively long etch times to create an air gap under the device.

[0014] These and other objects of the present invention will become apparent to those skilled in the art from the following detailed description of the invention and the accompanying drawings.

Summary of the Invention

[0015] The present invention is an acoustical resonator and a method for making the same. A resonator according to the present invention includes a layer of piezoelectric material sandwiched between first and second electrodes. The first electrode includes a conducting sheet having a RMS variation in height of less than 2 μm . The resonator bridges a cavity in the substrate on which the resonator is constructed. The resonator is constructed by creating a cavity in the substrate and filling the same with a sacrificial material that can be rapidly removed from the cavity after the deposition of the various layers making up the resonator. The surface of the filled cavity is polished to provide a RMS variation in height of less than 0.5 μm . A first electrode is deposited on the polished surface to a thickness that assures that the RMS variation in height of the metallic layer is less than 2 μm . The piezoelectric layer is deposited on the first electrode and the second electrode is then deposited on the piezoelectric layer. The sacrificial material is then removed from the cavity by opening vias into the cavity and removing the material through the vias. The preferred sacrificial material is phosphor-silica-glass.

Brief Description of the Drawings

[0016]

Figure 1 is a cross-section of FBAR resonator.

Figure 2 is a cross-section of an SBAR resonator.

Figures 3-7 are cross-sectional views of a portion of a wafer on which an FBAR is constructed by the method of the present invention

Detailed Description of the Invention

[0017] The present invention may be more easily understood with reference to Figures 1 and 2 which are cross-sectional views of an FBAR and an SBAR, respectively. Referring to Figure 1, FBAR 20 includes bottom and top electrodes 23 and 21, respectively, which sandwich a portion of a sheet of piezoelectric (PZ) material 22. The preferred PZ material is aluminum nitride, AlN. The electrodes used in resonator 20 are preferably made of molybdenum; however, embodiments employing other materials may also be constructed.

[0018] These devices use bulk longitudinal acoustic waves in the thin film PZ material. When an electric field is created between the two electrodes via an impressed voltage, the PZ material converts some of the electrical energy into mechanical energy in the form of sound waves. The sound waves propagate in the same direction as the electric field and reflect off of the electrode/air interface.

[0019] At the mechanical resonance, the device appears to be an electronic resonator; hence, the device can act as a notch filter. The mechanical resonant frequency is the frequency for which the half wavelength of the sound waves propagating in the device is equal to the total thickness of the device for a given phase velocity of sound in the material. Since the velocity of sound is many orders of magnitude smaller than the velocity of light, the resulting resonator can be quite compact. Resonators for applications in the GHz range may be constructed with physical dimensions of the order of 100 μm and few μm in thickness.

[0020] Refer now to Figure 2, which is a cross-sectional view of an SBAR 40. An SBAR provides electrical functions analogous to those of a band-pass filter. SBAR 40 is basically two FBAR filters that are mechanically coupled. A signal across electrodes 43 and 44 at the resonance frequency of PZ layer 41 will transmit acoustical energy to PZ layer 42. The mechanical oscillations in PZ layer 42 are converted to an electrical signal across electrodes 44 and 45 by the PZ material.

[0021] The manner in which an FBAR and SBAR are constructed according to the present invention may be more easily understood with reference to Figures 3-7 which are cross-sectional views of a portion of a wafer

101 on which an FBAR 110 is constructed by the method of the present invention. The present invention utilizes a sacrificial layer comprising a material that is much more easily etched than the thermal oxides utilized in prior art methods based on sacrificial layers. In the preferred embodiment of the present invention, the sacrificial layer is constructed from phosphor-silica-glass (PSG).

[0022] Referring to Figure 3, a pit 102 is etched into substrate 101 which is preferably a conventional silicon wafer of the type utilized in integrated circuit fabrication. The pit is preferably less than 30 μm . It should be noted that the depth of the cavity under the FBAR needs to be only sufficient to accommodate the displacement created by the piezoelectric layer. Hence, a pit having a depth of a few μm is sufficient.

[0023] A thin layer of thermal oxide 103 is grown on the surface of the wafer to prevent phosphorous from the PSG from diffusing into the layer. Such diffusion would convert the silicon to a conductor, which would interfere with the electrical operation of the final device.

[0024] Referring to Figure 4, a PSG layer is then deposited over the wafer. The PSG is deposited at a temperature of $\sim 450^\circ\text{C}$ using a silane and P_2O_5 sources to form a soft glass like material which is approximately 8% phosphorous. This low temperature process is well known to those skilled in the art, and hence, will not be discussed in detail here. The PSG is the preferred choice for a sacrificial layer because it is a very clean, inert material that can be deposited at the relatively low temperature and can be etched in a dilute $\text{H}_2\text{O}:\text{HF}$ solution at a very high etch rate. At a dilution ratio of 10:1, etch rates on the order of 3 μm per minute are obtained.

[0025] Unfortunately, a native PSG sacrificial layer is a poor base for constructing an acoustical resonator. At the atomic level the surface of such deposited films are atomically very rough. An acoustical resonator of the FBAR/SBAR type requires a piezoelectric material in which the crystals grow in columns that are perpendicular to the plane of the electrodes. Attempts to grow well-collimated piezoelectric films on the surface of a PSG layer result, at best, in poor polycrystalline material that exhibits little or no piezoelectric effects because the many facets on the rough surface initiate crystal growth in a variety of directions.

[0026] The present invention overcomes this difficulty by polishing the PSG surface to provide an atomically smooth surface. Referring to Figure 5, the surface of the PSG layer 105 is first planarized by polishing with a slurry to remove the portion of the PSG layer outside of pit 102. The remaining PSG can then be polished using a more refined slurry. Alternatively, a single more refined slurry can be used for both polishing steps if the additional polishing time is not objectionable. The goal is to create a "mirror" like finish.

[0027] The cleaning of these wafers is also critical. The slurry will leave bits of silica grit on the wafer. This grit must be removed. In the preferred embodiment of

the present invention, this is accomplished by using a second polishing wheel with a stiff, hard pad such as Polytex™ (Rodel, Connecticut) De-ionized water is used as the lubricant. After being polished, the wafers are kept in de-ionized water until ready for the final cleaning step. The wafers should not be allowed to dry between the last polish step and the last cleaning step. The last cleaning step consists of dipping the wafers in a series of tanks that hold various chemicals. Each tank is subjected to ultrasonic agitation. Such cleaning benches we well known to the art, and hence, will not be discussed in detail here. A cleaning bench of the Megasonic™ type available from Ameramade, California U.S.A. has been found to be adequate.

[0028] The present invention is based on the surprising finding that such a smooth surface provides a base for the deposition of highly textured c-axis piezoelectric material demonstrating excellent piezoelectric properties in spite of the fact that it does not contain a crystalline structure that "seeds" the piezoelectric layer.

[0029] The grit consists of silica particulates. In the preferred embodiment of the present invention, a slurry made by Rodel (#1508) which is an ammonia based slurry of silica particulates is utilized.

[0030] While the above discussion has indicated a specific polishing and cleaning regime, any polishing and cleaning regime which provides a surface of the requisite smoothness may be utilized. In the preferred embodiment of the present invention, the final surface has a RMS (root-mean-squared) variation in height of less than 0.5 μm as measured with an atomic force microscope probe.

[0031] After the surface is cleaned, the bottom electrode 111 of the FBAR 110 is deposited as shown in Figure 6. The preferred electrode material is molybdenum; However, other materials will be apparent to those skilled in the art. For example, the electrodes may be constructed from Al, W, Au, Pt, or Ti. Molybdenum is preferred because of its low thermo-elastic loss. For example, Mo has approximately 56 times less thermo-elastic loss than Al.

[0032] The thickness of the bottom electrode is also important. Thicker layers are rougher than thinner layers. As noted above, maintaining a smooth surface for the deposition of the piezoelectric layer is crucial to the performance of the final resonator. Hence, the thickness of the bottom electrode is preferably less than 1000 Å. The Mo is preferably deposited utilizing sputtering. This provides a Mo layer that has a RMS variation in height of less than 2 μm .

[0033] After the bottom electrode has been deposited, the piezoelectric layer 112 is deposited. The preferred material for the piezoelectric layer is AlN, which is also deposited by sputtering. Since the deposition of AlN to form a piezoelectric layer is well known in the art, this deposition process will not be discussed in detail here. In the preferred embodiment of the present invention, the piezoelectric layer has a thickness between 0.1 and

10 μm .

[0034] Finally, the top electrode 113 is deposited. The top electrode is also preferably constructed from Mo. However, the thickness of this electrode is less critical, since it does not influence the deposition of the piezoelectric layer.

[0035] After the FBAR structure is deposited, vias are opened to the underlying sacrificial layer 105 and the PSG removed by etching in dilute $\text{H}_2\text{O}:\text{HF}$ solution as shown in Figure 7. This leaves FBAR 110 suspended over the original pit 102.

[0036] The above example has utilized the construction of an FBAR. However, it will be obvious to those skilled in the art from the preceding discussion that an SBAR can be constructed utilizing the same process. In the case of an SBAR, an additional piezoelectric layer and electrode must be deposited. Since the second piezoelectric layer is constructed on the top electrode of the "FBAR", the thickness of the top electrode must also be kept to $< 1000 \text{ \AA}$ to provide a suitable surface for depositing the second piezoelectric layer.

[0037] While the above-described embodiments of the present invention utilize a sacrificial layer constructed from PSG, other materials may also be used. For example, other forms of glass such as BPSG or spin-on-glass may be utilized. In addition, there are plastics such as polyvinyl, polypropylene and polystyrene that can be deposited either by spinning on the material or depositing in special chambers. These sacrificial layers can be removed using an organic stripper or O_2 plasma etch. As with the PSG sacrificial layer, polishing is also crucial with these materials, as the surfaces of these materials as deposited are not atomically smooth.

[0038] Various modifications to the present invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Accordingly, the present invention is to be limited solely by the scope of the following claims.

Claims

1. An acoustical resonator[20, 40, 110] comprising: a first electrode[23, 45, 111] comprising a conducting sheet having a RMS variation in height of less than $2 \mu\text{m}$; a second electrode[21, 44, 113] comprising a conducting sheet; a layer of piezoelectric material[22, 42, 112] sandwiched between said first and second electrodes.
2. The acoustical resonator[20, 40, 110] of Claim 1 wherein said first electrode[23, 45, 111] comprises molybdenum.
3. The acoustical resonator[20, 40, 110] of Claim 1 or 2 wherein said layer of piezoelectric material[22, 42, 112] comprises AlN.
4. The acoustical resonator[20, 40, 110] of one of the

preceding Claims further comprising a substrate[101] having a cavity[102] in a surface thereof, said first electrode[23, 45, 111] bridging said cavity[102].

5. The acoustical resonator[20, 40, 110] of Claim 4 wherein said cavity[102] is less than $30 \mu\text{m}$ deep.
6. The acoustical resonator[20, 40, 110] of Claim 4 or 5 wherein said surface of said substrate[101] comprises an electrically insulating layer[103].
7. A method for fabricating an acoustical resonator[20, 40, 110] on a substrate[101] having a top surface, said method comprising steps of: generating a depression[102] in said top surface; filling said depression[102] with a sacrificial material [105], said filled depression[102] having an upper surface level with said top surface of said substrate[101], said upper surface having a RMS variation in height of less than $0.5 \mu\text{m}$; depositing a first electrode[23, 45, 111] on said upper surface; depositing a layer of piezoelectric material[22, 42, 112] on said first electrode[23, 45, 111]; depositing a second electrode[21, 44, 113] on said layer of piezoelectric material[22, 42, 112]; and removing said sacrificial material [105] from said depression[102].
8. The method of Claim 7 wherein said sacrificial material [105] comprises a material chosen from the group consisting of PSG, BPSG, spin-on-glass, polyvinyl, polypropylene and polystyrene.
9. The method of Claim 7 or 8 wherein said step of filling said depression[102] comprises the steps of: depositing a layer of said sacrificial material [105] over said depression[102]; planarizing said deposited layer; and polishing said planarized layer.
10. The method of Claim 9 further comprising the step of providing a layer of an electrically insulating material[103] on the surface of said substrate[101] and depression[102] prior to depositing said layer of sacrificial material [105], said electrically insulating material preventing a diffusion of elements in said sacrificial material [105] from diffusing into said substrate[101].
11. The method of one of Claims 7 - 10 wherein said first electrode[23, 45, 111] comprises molybdenum.
12. The method of one of Claims 7 - 11 wherein said layer of piezoelectric material[22, 42, 112] comprises AlN.
13. The method of one of Claims 7 - 12 wherein said depression[102] is less than $30 \mu\text{m}$ deep.

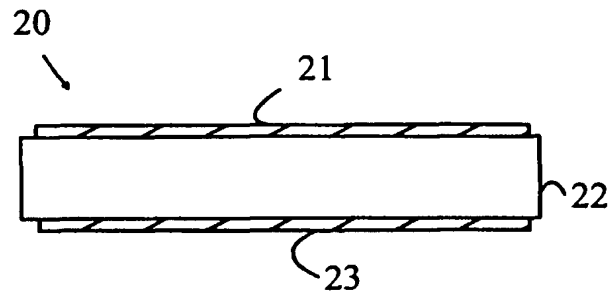


FIGURE 1

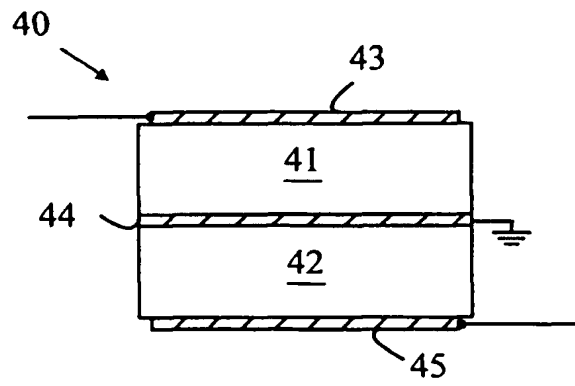


FIGURE 2

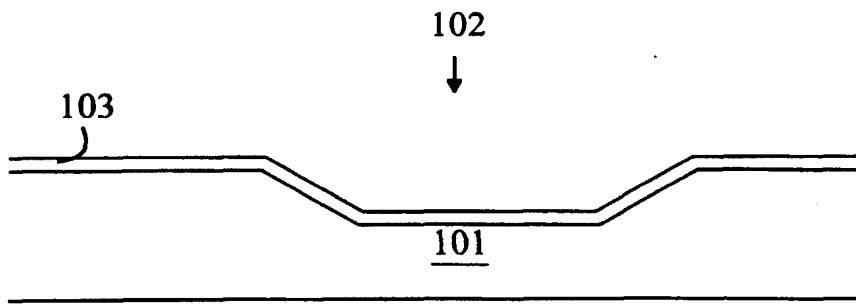


FIGURE 3

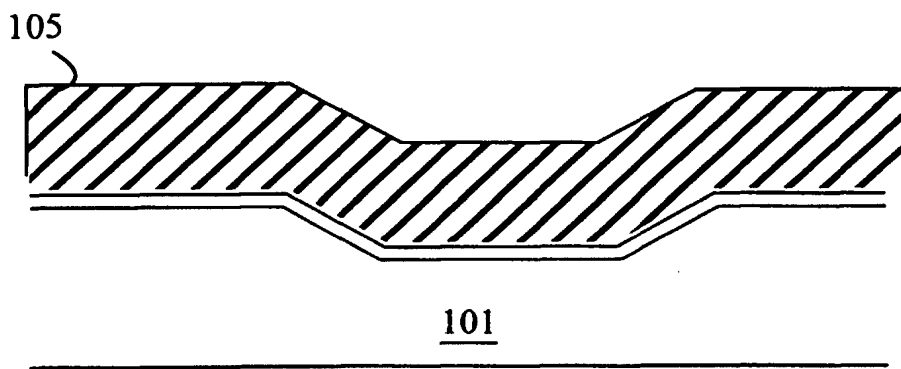


FIGURE 4

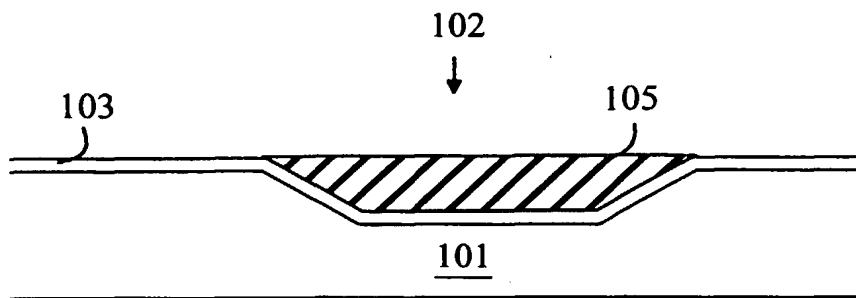


FIGURE 5

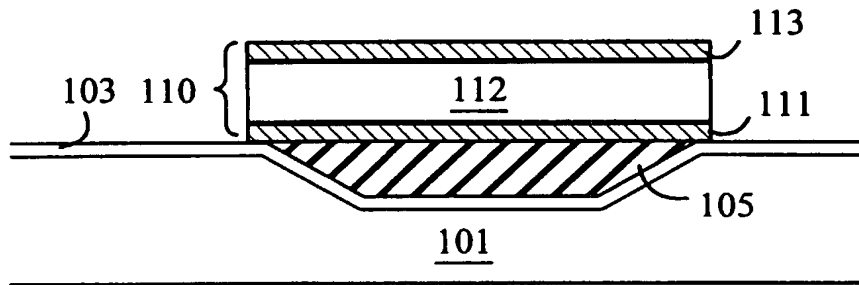


FIGURE 6

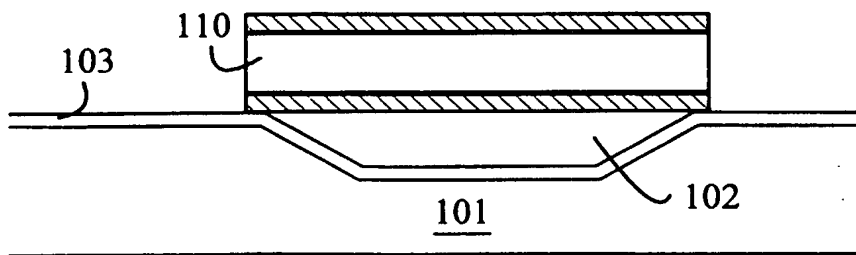
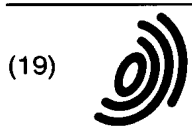


FIGURE 7



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(11) **EP 0 963 040 A3**

(12) **EUROPEAN PATENT APPLICATION**

(88) Date of publication A3:
05.04.2000 Bulletin 2000/14

(51) Int. Cl.7: **H03H 9/17, H03H 3/02**

(43) Date of publication A2:
08.12.1999 Bulletin 1999/49

(21) Application number: **99104070.0**

(22) Date of filing: **17.03.1999**

(84) Designated Contracting States:
**AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
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AL LT LV MK RO SI

(30) Priority: **02.06.1998 US 88964**

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polished to provide a RMS variation in height of less than 0.5 µm. The first electrode[23, 45, 111] is deposited on the polished surface to a thickness that assures that the RMS variation in height of the metallic layer is less than 2 µm. The piezoelectric layer is deposited on the first electrode[23, 45, 111] and the second electrode[21, 44, 113] is then deposited on the piezoelectric layer. The sacrificial material [105] is then removed from the cavity[102] by opening vias into the cavity[102] and removing the material through the vias. The preferred sacrificial material [105] is phosphor-silica-glass.

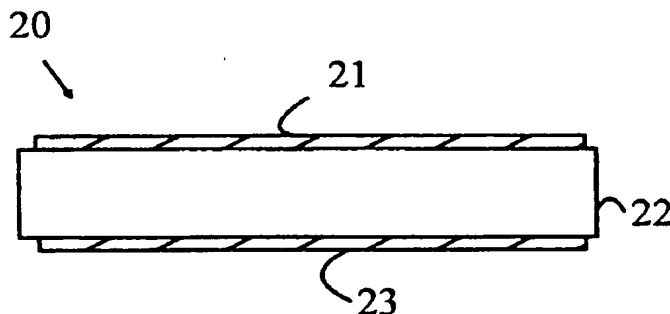


FIGURE 1

EP 0 963 040 A3



European Patent
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EUROPEAN SEARCH REPORT

Application Number
EP 99 10 4070

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	WO 98 16956 A (NOKIA MOBILE PHONES LTD ;NOKIA MOBILE PHONES INC (US)) 23 April 1998 (1998-04-23) * page 13, line 17 - page 14, line 28; claim 1; figures *	1,4,7-10	H03H9/17 H03H3/02
A	US 5 666 706 A (KANABOSHI AKIHIRO ET AL) 16 September 1997 (1997-09-16) * column 5, line 31 - column 6, line 22; figures 2A-2F *	1,4,7	
A	EP 0 771 070 A (MITSUBISHI ELECTRIC CORP) 2 May 1997 (1997-05-02) * page 16, line 39 - page 17, line 17; figures 9,10 *	1,4,7	
A	RUBY R: "Micromachined cellular filters" 1996 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST (CAT. NO.96CH35915), 1996 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST, SAN FRANCISCO, CA, USA, 17-21 JUNE 1996, pages 1149-1152 vol.2, XP002129905 1996, New York, NY, USA, IEEE, USA ISBN: 0-7803-3246-6 * page 1151, left-hand column, line 10 - line 26 *	1,4,7	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			H03H
The present search report has been drawn up for all claims			
Place of search	Date of completion of the search	Examiner	
THE HAGUE	7 February 2000	D/L PINTA BALLE., L	
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document</p>			

EPO FORM 1503 03.82 (P04C01)



European Patent
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EUROPEAN SEARCH REPORT

Application Number
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A	<p>SEABURY C W ET AL: "High performance microwave air-bridge resonators" 1995 IEEE ULTRASONICS SYMPOSIUM. PROCEEDINGS. AN INTERNATIONAL SYMPOSIUM (CAT. NO.95CH35844), 1995 IEEE ULTRASONICS SYMPOSIUM. PROCEEDINGS. AN INTERNATIONAL SYMPOSIUM, SEATTLE, WA, USA, 7-10 NOV. 1995, pages 909-911 vol.2, XP002129906 1995, New York, NY, USA, IEEE, USA ISBN: 0-7803-2940-6</p> <p>* page 910, left-hand column, line 6 - line 35; figure 3 *</p> <p>-----</p>	1,4,7	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
THE HAGUE		7 February 2000	D/L PINTA BALLE..., L
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons</p> <p>& : member of the same patent family, corresponding document</p>			

EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 99 10 4070

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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